A FRAMEWORK FOR DESIGN OF REMANUFACTURABLE PRODUCTS

Submitted by

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ABSTRACT

Among the four End-of-Life (EoL) Options – Repair, Recycle, Reconditioning and Remanufacturing, Remanufacturing is widely recognized as the most effective strategy for gaining a competitive edge, and it is encouraged by government programmes in western nations. Original Equipment Manufacturer's (OEM) take the effort to build a new product addressing the needs of the customer and form a supply chain to distribute it widely. Nevertheless, when the OEM's are less accessible, third party manufacturer's build independent facilities for offering services to used product. However, OEM's can offer the best reliable remanufactured product if they incorporate the goal of multiple life cycles from the first design phase. The automotive sector is the most effective remanufacturing product area which has been around for many years. The manufacturing facilities and distribution facilities have a big geographical widespread globally. The most effective change management is possible if OEM's support their designers in understanding the benefits obtained through remanufacturing for all the stakeholders. End product user is supposed to be the key stakeholder. For an OEM looking out for sustainable remanufacturing practices, the end-user is not only the customer of new and remanufactured product, but also the supplier of the used product. While the new product may address the needs of the customer, setting the benchmark, the remanufactured product should offer the same standards while valuing the used product returned by customer appropriately. The quality evaluation of new, used and remanufactured stages of the product can be planned through designing a multiple life-cycle product from first stage itself. Various quality tools have been developed to assist designers as per the design objectives. The aim of the research is to understand the problem of design assessment investigating the design factors and key drivers contributing to success of remanufacturability, thus giving better support to design tools.

The various design elements that have been under consideration for improving different facets of remanufacturing are investigated and their relevance in industry is examined through a comprehensive study of working of successful organizations. The success parameters that drive the inputs and activities for the process are essential to be identified. The recommended method to examine the commonalities inherent in organizational working styles is through exploratory research. The research attempts to derive results in the form of empirical relationships. A framework to meet the requirements

as per the transitioning role of the customer through different phases of remanufacturing cycle is attempted for OEM designers. The endeavor of the framework is to provide a guidelines to be applied from the first stage of product development, by carrying out a study on the best practices followed in successful remanufacturing organizations in developed countries.

The framework is developed using an integrated research process that combines three structural modelling techniques for constructing, assessing and comprehending it. After gauging significance of design elements and drivers an initial model is constructed through DEMATEL (Decision Making and Trial Evaluation Laboratory) by identifying cause-effect relationships. It provides the point of reference for improving the model further by numerous systematic iterations of relationships between design factors and drivers.

For evaluation of these iterations, Structural Equation Modeling – a robust amalgamation of Confirmatory Factor Analysis and multiple regression techniques for path analysis is used. The technique first evaluates the validity of categorization and subsequently tests the reliability of relationships through indices. The final multivariate model consists of 19 validated hypotheses.

The structural model is made fit for use by OEM designers through the application of Interpretive Structural Modeling. In the process, the constructs get ordered as per their driving and dependence power emerging from prioritized relationships, resulting in the recommendation of a framework of concurrent design for remanufacturable products. The examination of the model's nonlinear interactions shows that in the long term, with the appropriate approach, they can help remanufacturing succeed over time.

Keywords: *Design for Remanufacturing, OEM designers, Structural Equation Modeling, Structural Modeling, DEMATEL, Product Design*

INTRODUCTION

2.1. DESIGN FOR REMANUFACTURING

When a product, being used starts being dysfunctional or obsolete, it is said to be nearing its End-of- Life (EoL). It may then be submitted for Repairing, Reconditioning, Recycling or Remanufacturing. Remanufacturing has become the most advocated End-Of-Life options carried out by Original Equipment Manufacturer's (OEM's) and 3rd Party Remanufacturers as the product is required to be made as good as new. To accomplish this, the earliest stage of change through which maximum long-term advantage can be achieved is the "Design" stage where the designers of the Original Equipment Manufacturer (OEM) work on developing product for end-user. As is observed further, the current tools are of limited use and appropriate guidance to the OEM Designers for an all-inclusive approach for multi-life cycle design is lacking. For remanufacturing to be successful, the Socio –economic drivers need to be addressed. The current study is an attempt to provide guidance at design stage to align the technical aspects with the drivers.

2.2. FOREMOST EXISTING DESIGN TOOLS

In 1995, an attempt to identify the characteristics of the product which could improve its Remanufacturability and recommended design changes in an Automobile door was made [1]. In 1996 they developed the first quantitative Remanufacturability Index assessing the product design based on Metrics [2]. A survey on the issues affecting the remanufacturing steps helped infer that a uniform ranking was difficult and a scope for customization in metrics is essential [3]. The metrics have been attempted to be used and developed to apply for possible valuable deductions [4-15]. In 2004, RemPro matrix was developed which related Product properties to Remanufacturing Operations [16]. Further illustrations on its use was done by the authors via case studies [17-31]. Remanufacturing Product Profile – Re-PRO^2 tool was developed based on an analysis of different successfully remanufactured products [32]. The literature provides directions on utility of this tool by use of core, internal and external variables of the product being considered employing a match making algorithm in the background [33-39].

Charter M. and Casper G. (2008) came up with a matrix interrelating the Design for X strategies such as Design for Assembly, Design for upgrade with Remanufacturing process steps [40]. Studies on aligning the Design for X approach to support remanufacturing are being done to guide the designers over a period of time [41-50].

Table 2.1 gives a brief summary of the design tools and their limitations.

Table 2.1: Current Design Tools for Remanufacutring

Design Aid	**Description**	**Authors**	**Limitation and Research Gaps**
Design for Remanufacturing Metrics	Ratios to compare Remanufacturing traits of Part Interfacing, Quality Assurance, Cleaning and Damage Correction	Bras and Hammond (1996), Ali Ammar et al.(2022)	Tool is retrospective in nature and cannot be applied at prototyping stage
REMPRO Matrix	It provides an insight into relationship between the Remanufacturing Steps and Product Properties	Sundin E.. (2004), Zhang X. et al.(2019)	Relationships are not based on quantitative assessment, lacking an insight in prioritisation
RePRO2 Tool	Tool based matches the product characteristics with 11 successful Remanufacturable Product Profiles in order to suggest the best match whose strategies might be adopted	Zwolinski et al. (2006), Zwolinski et. al.(2008), Linder M. et al.(2019)	The tool can be applied only when the product has reached Growth or Maturity stage of Product Life Cycle
Design for "X" Strategies	This matrix indicates the relationships between various design goal and Remanufacturing Steps	Charter M. and Casper G. (2008),Sassanelli et. al (2020)	The assessment of the strength of the relationships is lacking

Considering the limitations of the existing tools the Objectives and Hypothesis of the next chapter were worked out.

3.1 OBJECTIVE OF THE WORK

To achieve the aim of developing a framework of providing support to the design assessment of product at first stage of new product development to drive successful remanufacturing, the objectives for the research process involved are stated below:

1. To examine the methods and tools which help assess design remanufacturability.
2. To identify the requirements and factors used in assessing the product design for remanufacturability.
3. To design a framework to support assessment of remanufacturability at prototyping stage.
4. Test validity of the proposed framework and interpret it.

3.2 HYPOTHESES

The study identifies Financial Benefits(fb), End-of-Life Responsibility(el) and Remanufacturing Market needs (rm) as the three major driver categories while design considerations are grouped into six categories of a) Core Quality(cq), b) Interfacing(it), c) Quality Assurance(qa), d) Damage Correction(dc), e) Logistics(lg), and f) Product Design(pd). Four major Hypothesis and their sub-hypothesis are thus formulated as follows:

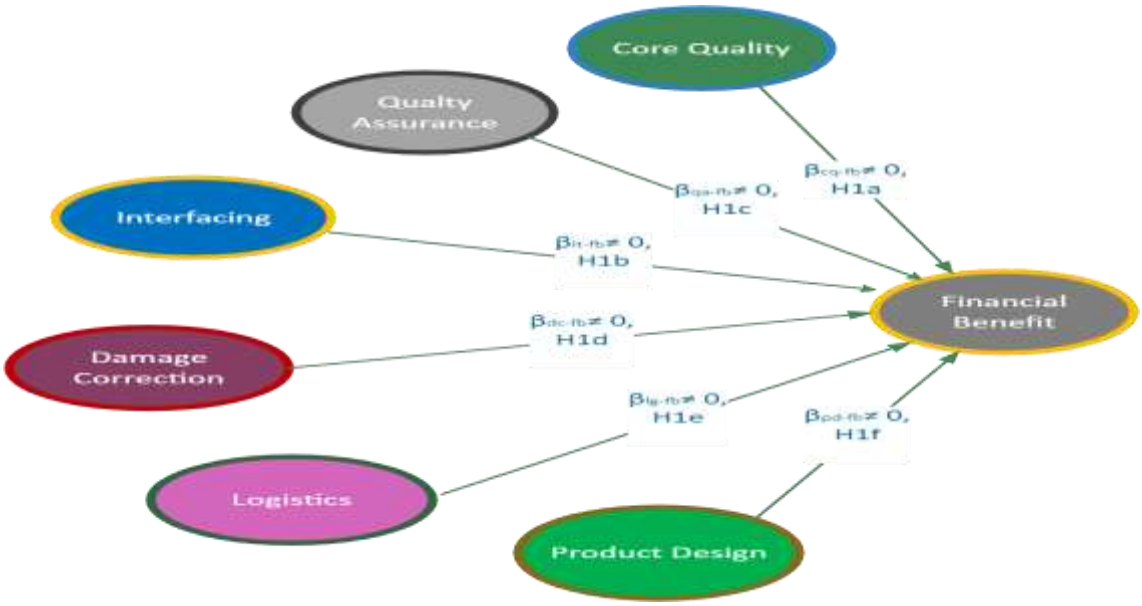

Figure 3.1 Hypothesis 1 – Relation of financial benefit driver with design factors

Hypothesis 1 (H1) - Design considerations at new product development stage significantly affects remanufacturing of the product with respect to financial benefits.

$H_{00} : \beta_{i\text{-}fb} = 0$

else

$H_{11} : \beta_{i\text{-}fb} \neq 0$

i: Design Factor under consideration;

$\beta_{i\text{-}fb}$: Path coefficient of effect of i^{th} Design consideration on Financial Benefit Driver

Hypothesis ($H1_a$) - Core Quality Design factor at new product development stage significantly affects remanufacturing of the product with respect to Financial Benefits.

$H_{01a} : \beta_{cq\text{-}fb} = 0$

else

$H_{11a} : \beta_{cq\text{-}fb} \neq 0$

Hypothesis ($H1_b$) - Interfacing Design factor at new product development stage significantly affects remanufacturing of the product with respect to Financial Benefits.

$H_{01b} : \beta_{it\text{-}fb} = 0$

else

$H_{11b} : \beta_{it\text{-}fb} \neq 0$

Hypothesis ($H1_c$) - Quality Assurance Design factor at new product development stage significantly affects remanufacturing of the product with respect to Financial Benefits

$H_{01c} : \beta_{qa\text{-}fb} = 0$

else

$H_{11c} : \beta_{qa\text{-}fb} \neq 0$

Hypothesis ($H1_d$) - Damage Correction Design factor at new product development stage significantly affects remanufacturing of the product with respect to o Financial Benefits

$H_{01d} : \beta_{dc\text{-}fb} = 0$

else

$H_{11d} : \beta_{dc\text{-}fb} \neq 0$

Hypothesis ($H1_e$) - Logistics Design factor at new product development stage significantly affects remanufacturing of the product with respect to Financial Benefits.

$H_{01e} : \beta_{lg\text{-}fb} = 0$

else

H_{11e} : $\beta_{lg\text{-}fb} \neq 0$

Hypothesis ($H1_f$) - Product Design factor at new product development stage significantly affects remanufacturing of the product with respect to Financial Benefits.

H_{01f} : $\beta_{pd\text{-}fb} = 0$

else

H_{11f} : $\beta_{pd\text{-}fb} \neq 0$

Similarly, the sub-hypothesis may be written for H2 and H3.

Hypothesis 2 (H2) - Design considerations at new product development stage significantly affects remanufacturing of the product with respect to addressing end-of-life responsibility.

Hypothesis 3 (H3) - Design Considerations at new product development stage significantly affects remanufacturing of the product with respect to addressing the remanufacturing market needs.

Hypothesis 4 (H4) – Design Factors and Drivers of remanufacturing are significantly interrelated.

H_{00} : $\beta_{i\text{-}j} = 0$

else

H_{14} : $\beta_{i\text{-}j} \neq 0$

i: Factor treated as exogenous variable;

$\beta_{i\text{-}j}$: Path coefficient of effect of i^{th} factor on j^{th} factor

Hypothesis 4 (H4) – Design Factors and Drivers have significant interrelationships: All possible 54 sub-hypothesis arising from Hypothesis 4 are represented in below Table:

		j --->								
		Financial Benefit(fb)	EoL Responsibility(el)	Rmfg. Mkt. Needs(rm)	Core Quality(cq)	Interfacing(it)	Quality Assurance(qa)	Damage Correction(dc)	Logistics(lg)	Product Design(pd)
i -->	Financial Benefit(fb)		$H04_{f\text{-}e}$: $\beta_{fb\text{-}el}=0$ $H14_{\mathbf{f\text{-}e}}$: $\beta_{fb\text{-}el}\neq 0$	$H04_{f\text{-}r}$: $\beta_{fb\text{-}rm}=0$ $H14_{\mathbf{f\text{-}r}}$: $\beta_{fb\text{-}rm}\neq 0$	$H04_{f\text{-}c}$: $\beta_{fb\text{-}cq}=0$ $H14_{\mathbf{f\text{-}c}}$: $\beta_{fb\text{-}cq}\neq 0$	$H04_{f\text{-}i}$: $\beta_{fb\text{-}it}=0$ $H14_{\mathbf{f\text{-}i}}$: $\beta_{fb\text{-}it}\neq 0$	$H04_{f\text{-}q}$: $\beta_{fb\text{-}qa}=0$ $H14_{\mathbf{f\text{-}q}}$: $\beta_{fb\text{-}qa}\neq 0$	$H04_{f\text{-}d}$: $\beta_{fb\text{-}dc}=0$ $H14_{\mathbf{f\text{-}d}}$: $\beta_{fb\text{-}dc}\neq 0$	$H04_{f\text{-}l}$: $\beta_{fb\text{-}lg}=0$ $H14_{\mathbf{f\text{-}l}}$: $\beta_{fb\text{-}lg}\neq 0$	$H04_{f\text{-}p}$: $\beta_{fb\text{-}pd}=0$ $H14_{\mathbf{f\text{-}p}}$: $\beta_{fb\text{-}pd}\neq 0$
	EoL Responsibility(el)	$H04_{e\text{-}f}$: $\beta_{el\text{-}fb}=0$ $H14_{\mathbf{e\text{-}f}}$: $\beta_{el\text{-}fb}\neq 0$		$H04_{e\text{-}r}$: $\beta_{el\text{-}rm}=0$ $H14_{\mathbf{e\text{-}r}}$: $\beta_{el\text{-}rm}\neq 0$	$H04_{e\text{-}c}$: $\beta_{el\text{-}cq}=0$ $H14_{\mathbf{e\text{-}c}}$: $\beta_{el\text{-}cq}\neq 0$	$H04_{e\text{-}i}$: $\beta_{el\text{-}it}=0$ $H14_{\mathbf{e\text{-}i}}$: $\beta_{el\text{-}it}\neq 0$	$H04_{e\text{-}q}$: $\beta_{el\text{-}qa}=0$ $H14_{\mathbf{e\text{-}q}}$: $\beta_{el\text{-}qa}\neq 0$	$H04_{e\text{-}d}$: $\beta_{el\text{-}dc}=0$ $H14_{\mathbf{e\text{-}d}}$: $\beta_{el\text{-}dc}\neq 0$	$H04_{e\text{-}l}$: $\beta_{el\text{-}lg}=0$ $H14_{\mathbf{e\text{-}l}}$: $\beta_{el\text{-}lg}\neq 0$	$H04_{e\text{-}p}$: $\beta_{el\text{-}pd}=0$ $H14_{\mathbf{e\text{-}p}}$: $\beta_{el\text{-}pd}\neq 0$
	Rmfg. Mkt. Needs(rm)	$H04_{r\text{-}f}$: $\beta_{rm\text{-}fb}=0$ $H14_{\mathbf{r\text{-}f}}$: $\beta_{rm\text{-}fb}\neq 0$	$H04_{r\text{-}e}$: $\beta_{rm\text{-}el}=0$ $H14_{\mathbf{r\text{-}e}}$: $\beta_{rm\text{-}el}\neq 0$		$H04_{r\text{-}c}$: $\beta_{rm\text{-}cq}=0$ $H14_{\mathbf{r\text{-}c}}$: $\beta_{rm\text{-}cq}\neq 0$	$H04_{r\text{-}i}$: $\beta_{rm\text{-}it}=0$ $H14_{\mathbf{r\text{-}i}}$: $\beta_{rm\text{-}it}\neq 0$	$H04_{r\text{-}q}$: $\beta_{rm\text{-}qa}=0$ $H14_{\mathbf{r\text{-}q}}$: $\beta_{rm\text{-}qa}\neq 0$	$H04_{r\text{-}d}$: $\beta_{rm\text{-}dc}=0$ $H14_{\mathbf{r\text{-}d}}$: $\beta_{rm\text{-}dc}\neq 0$	$H04_{r\text{-}l}$: $\beta_{rm\text{-}lg}=0$ $H14_{\mathbf{r\text{-}l}}$: $\beta_{rm\text{-}lg}\neq 0$	$H04_{r\text{-}p}$: $\beta_{rm\text{-}pd}=0$ $H14_{\mathbf{r\text{-}p}}$: $\beta_{rm\text{-}pd}\neq 0$
	Core Quality(cq)	**Hypothesis1 : Design Considerations have a significant effect on Financial Benefits**	**Hypothesis2 : Design Considerations have a significant effect on addressing EoL Responsibility**	**Hypothesis3 : Design Considerations have a significant effect on addressing Remanufacturing Market Needs**		$H04_{c\text{-}i}$: $\beta_{cq\text{-}it}=0$ $H14_{\mathbf{c\text{-}i}}$: $\beta_{cq\text{-}it}\neq 0$	$H04_{c\text{-}q}$: $\beta_{cq\text{-}qa}=0$ $H14_{\mathbf{c\text{-}q}}$: $\beta_{cq\text{-}qa}\neq 0$	$H04_{c\text{-}d}$: $\beta_{cq\text{-}dc}=0$ $H14_{\mathbf{c\text{-}d}}$: $\beta_{cq\text{-}dc}\neq 0$	$H04_{c\text{-}l}$: $\beta_{cq\text{-}lg}=0$ $H14_{\mathbf{c\text{-}l}}$: $\beta_{cq\text{-}lg}\neq 0$	$H04_{c\text{-}p}$: $\beta_{cq\text{-}pd}=0$ $H14_{\mathbf{c\text{-}p}}$: $\beta_{cq\text{-}pd}\neq 0$
	Interfacing(it)				$H04_{i\text{-}c}$: $\beta_{it\text{-}cq}=0$ $H14_{\mathbf{i\text{-}c}}$: $\beta_{it\text{-}cq}\neq 0$		$H04_{i\text{-}q}$: $\beta_{it\text{-}qa}=0$ $H14_{\mathbf{i\text{-}q}}$: $\beta_{it\text{-}qa}\neq 0$	$H04_{i\text{-}d}$: $\beta_{it\text{-}dc}=0$ $H14_{\mathbf{i\text{-}d}}$: $\beta_{it\text{-}dc}\neq 0$	$H04_{i\text{-}l}$: $\beta_{it\text{-}lg}=0$ $H14_{\mathbf{i\text{-}l}}$: $\beta_{it\text{-}lg}\neq 0$	$H04_{i\text{-}p}$: $\beta_{it\text{-}pd}=0$ $H14_{\mathbf{i\text{-}p}}$: $\beta_{it\text{-}pd}\neq 0$
	Quality Assurance(qa)				$H04_{q\text{-}c}$: $\beta_{qa\text{-}cq}=0$ $H14_{\mathbf{q\text{-}c}}$: $\beta_{qa\text{-}cq}\neq 0$	$H04_{q\text{-}i}$: $\beta_{qa\text{-}it}=0$ $H14_{\mathbf{q\text{-}i}}$: $\beta_{qa\text{-}it}\neq 0$		$H04_{q\text{-}d}$: $\beta_{qa\text{-}dc}=0$ $H14_{\mathbf{q\text{-}d}}$: $\beta_{qa\text{-}dc}\neq 0$	$H04_{q\text{-}l}$: $\beta_{qa\text{-}lg}=0$ $H14_{\mathbf{q\text{-}l}}$: $\beta_{qa\text{-}lg}\neq 0$	$H04_{q\text{-}p}$: $\beta_{qa\text{-}pd}=0$ $H14_{\mathbf{q\text{-}p}}$: $\beta_{qa\text{-}pd}\neq 0$
	Damage Correction(dc)				$H04_{d\text{-}c}$: $\beta_{dc\text{-}cq}=0$ $H14_{\mathbf{d\text{-}c}}$: $\beta_{dc\text{-}cq}\neq 0$	$H04_{d\text{-}i}$: $\beta_{dc\text{-}it}=0$ $H14_{\mathbf{d\text{-}i}}$: $\beta_{dc\text{-}it}\neq 0$	$H04_{d\text{-}q}$: $\beta_{dc\text{-}qa}=0$ $H14_{\mathbf{d\text{-}q}}$: $\beta_{dc\text{-}qa}\neq 0$		$H04_{d\text{-}l}$: $\beta_{dc\text{-}lg}=0$ $H14_{\mathbf{d\text{-}l}}$: $\beta_{dc\text{-}lg}\neq 0$	$H04_{d\text{-}p}$: $\beta_{dc\text{-}pd}=0$ $H14_{\mathbf{d\text{-}p}}$: $\beta_{dc\text{-}pd}\neq 0$
	Logistics(lg)				$H04_{l\text{-}c}$: $\beta_{lg\text{-}cq}=0$ $H14_{\mathbf{l\text{-}c}}$: $\beta_{lg\text{-}cq}\neq 0$	$H04_{l\text{-}i}$: $\beta_{lg\text{-}it}=0$ $H14_{\mathbf{l\text{-}i}}$: $\beta_{lg\text{-}it}\neq 0$	$H04_{l\text{-}q}$: $\beta_{lg\text{-}qa}=0$ $H14_{\mathbf{l\text{-}q}}$: $\beta_{lg\text{-}qa}\neq 0$	$H04_{l\text{-}d}$: $\beta_{lg\text{-}dc}=0$ $H14_{\mathbf{l\text{-}d}}$: $\beta_{lg\text{-}dc}\neq 0$		$H04_{l\text{-}p}$: $\beta_{lg\text{-}pd}=0$ $H14_{\mathbf{l\text{-}p}}$: $\beta_{lg\text{-}pd}\neq 0$
	Product Design(pd)				$H04_{p\text{-}c}$: $\beta_{pd\text{-}cq}=0$ $H14_{\mathbf{p\text{-}c}}$: $\beta_{pd\text{-}cq}\neq 0$	$H04_{p\text{-}i}$: $\beta_{pd\text{-}it}=0$ $H14_{\mathbf{p\text{-}i}}$: $\beta_{pd\text{-}it}\neq 0$	$H04_{p\text{-}q}$: $\beta_{pd\text{-}qa}=0$ $H14_{\mathbf{p\text{-}q}}$: $\beta_{pd\text{-}qa}\neq 0$	$H04_{p\text{-}d}$: $\beta_{pd\text{-}dc}=0$ $H14_{\mathbf{p\text{-}d}}$: $\beta_{pd\text{-}dc}\neq 0$	$H04_{p\text{-}l}$: $\beta_{pd\text{-}lg}=0$ $H14_{\mathbf{p\text{-}l}}$: $\beta_{pd\text{-}lg}\neq 0$	

CHAPTER 4

LITERATURE REVIEW

4.1 SCOPE OF THE THESIS

This thesis is an attempt to present the understandings developed from survey carried out on best practices followed in successful remanufacturing companies in automotive sector. The study uses DEMATEL to form the initial model via pilot study and then proceed further through Structural Equation Modeling to align design factors with drivers. Using Confirmatory Factor Analysis the model is tested for its robustness and is then converted into hierarchical form for ease of use.

4.2. DESIGN CONSIDERATIONS FOR REMANUFACTURING

Design for X (DfX) is a representation of indication a design approach having "X" as a priority. The numerous design considerations are interrelated.

A systematic methodology was employed used for literature survey. The list generated by the researcher were further put up for views from industry. To ascertain the presence of these factors in industry, different levels of experts having more than 5 years of experience were interviewed including engineering personnel, shop floor supervisors, design engineers and executive top management through online meetings. The respondents were from firms involved in manufacturing of blowers, air compressors and car engines. The opinions were sought on whether each of the 34 factors identified made a significant contribution in improving design to support incorporation of remanufacturability was probed. 17 factors contribute significantly in all the products, 5 factors to two products, 8 factors to one product while 4 factors were not found to be make any significant contribution in any of the products selected. Thus most of the factors identified in this study are relevant for industrial application. Open ended questions on classification of the factors in relation to the remanufacturing process helped categorize the factors into six groups : i) Core Quality, ii) Interfacing, iii) Damage Correction, iv) Quality Assurance, v) Product Design approach and vi) Logistics. This classification extends the four categories, first developed as metrics for Remanufacturability design [1].

4.3 DRIVERS FOR REMANUFACTURING

Numerous studies on drivers of remanufacturing have been done in different countries across different products [51-65]. As a part of the current research the changing expectations of the role of the end-user was considered. It was illustrated that the end-user transitions through three stages in the process of remanufacturing: i) Buyer of New Product, ii) Seller of Used Product & iii) Buyer of Remanufactured product. The expectations of the end-user change during these phases [66]. The drivers shown in figure 4.1 emerge from the needs of improving finance, taking up responsibility for the EoL product and meeting needs of remanufacturing market.

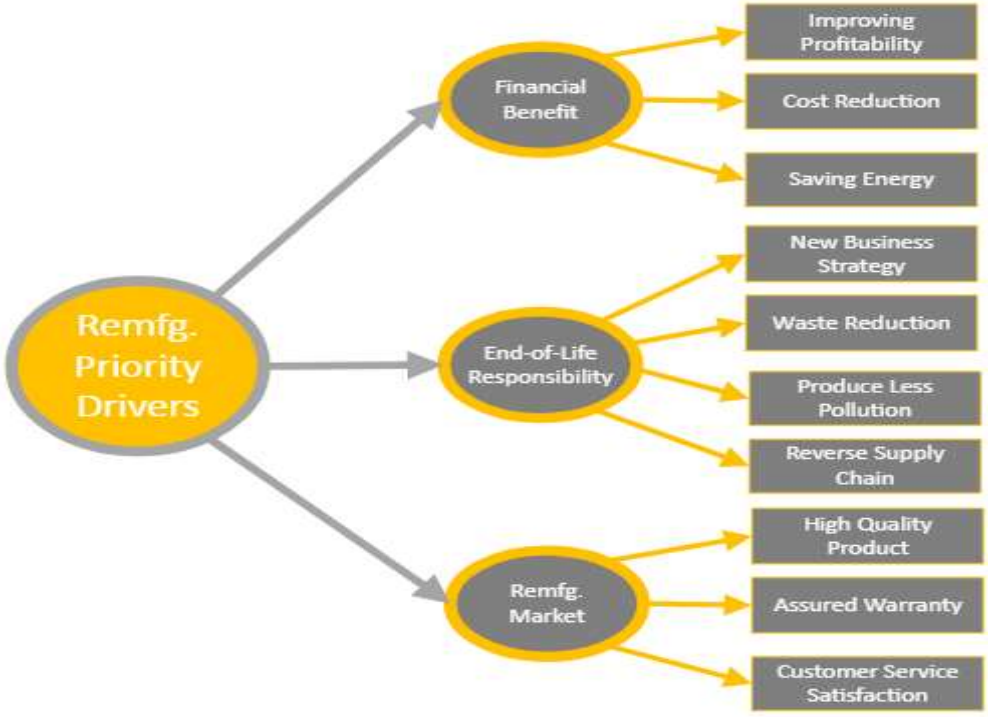

Figure 4.1 Drivers of success in remanufacturing

4.4. PROBLEM DEFINITION AND APPROACH

The aim of this research is to understand the problem of design assessment and determine what factors drive remanufacturing and how related design tools be better supported. Literature indicates several working cases where certain design considerations improve certain aspects of remanufacturability. These studies however fall short of addressing the holistic perspective and may also lead to bias of designer. Taking up remanufacturability as an organizational priority requires investigation of the design thinking for recognition of the drivers constituting the success of remanufacturing and design considerations that lead to achieving them. To support the assessment of product

design for improving remanufacturability its attempted to develop a framework by establishing the relationships between the design factors and drivers of successful remanufacturing. This is possible only through the analysis of the attributes in the best practices followed in successful remanufacturing organizations. The empirical research using survey methodology is recommended [162].

The structural modeling approach is applied in three stages for surveys carried out to apprehend the best practices in remanufacturing : 1) DEMATEL (Decision Making Trial and Evaluation Laboratory) is initially used to conceptualize the relationships between the construct and propose a framework. 2) Robust confirmatory factor analysis through Structural Equation Modeling is carried out to develop and validate the framework. 3) In the last step, Interpretive Structural Modeling is used to convert the framework into a usable Hierarchical model.

CHAPTER 5

CONTRIBUTION

After establishing the need for a framework to help OEM Designers to prioritize the design considerations to obtain maximum benefit for long term success of remanufacturing, this research contributes by addressing the need through an integration of three structural modeling techniques to not only derive the model but also provide a usable interpretation of the framework.

5.1 EXAMINING DRIVERS

For applying this methodology, in this study a survey was conducted among the marketing personnel of remanufacturing companies. The participants were asked to rank their agreement for each of the ten drivers listed on its importance as a critical factor influencing the remanufacturing adoption decision. The measure used was the 5 point Likert scale (1-Strongly Disagree, 2-Disagree, 3- Neutral, 4-Agree and 5 – Strongly Agree). The questionnaire was sent through mail to 34 on-field experts from companies of three different automotive sector products. 25 completed usable responses were received for further analysis. The distribution of responses of the professionals participating in the study, having 5 to 15 years of experience of serving the remanufactured product customers, is shown in figure 5.1.

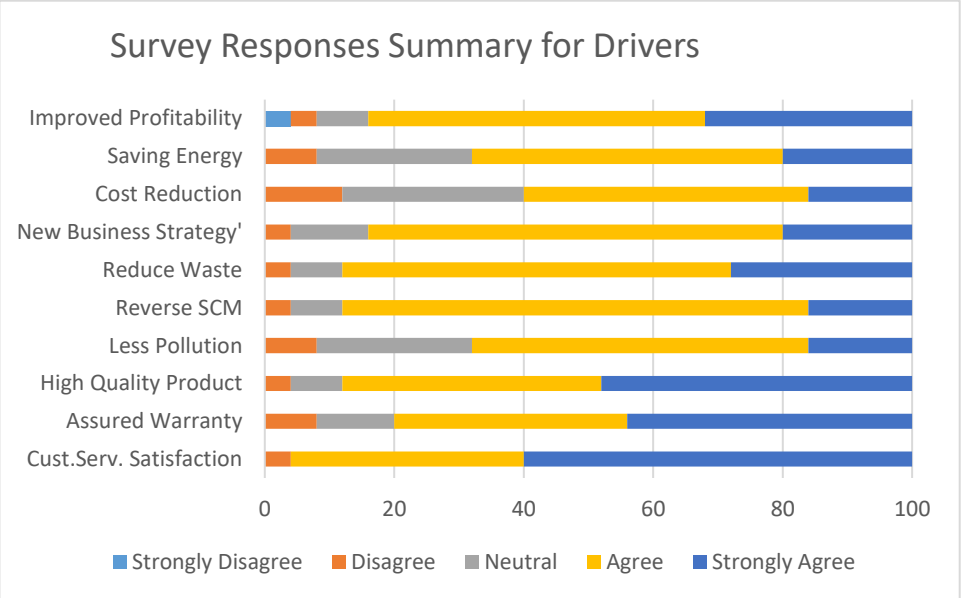

Figure 5.1 Distribution of agreement on significance of drivers

For determining the reliability of the survey instrument, the Cronbach alpha is computed. The threshold minimum value of Cronbach alpha acceptable in research is 0.7[67-70]. All the

values were found to be acceptable and above the 0.7. The data is thus reliable to proceed for calculation of the Signal to Noise Ratio.

Relative Importance Index (RII) for each factor was calculated. RII gives an insight into significance of factors by quantitatively analyzing the subjective ranking [71-78]. The second method of ranking is the Signal to Noise ratio used in literature to assess their behavior[79-85]. For this, Signal to Noise Ratio for each factor is calculated by using disagreement coefficient (P_{di}), agreement coefficient (P_{ai}) and the S/N ratios of corresponding coefficients n_{ai} and n_{di} are calculated and ranked accordingly. The spider graph of ranking of the drivers is shown in figure 5.2. The drivers closer to the center are most important as compared to those away from the center.

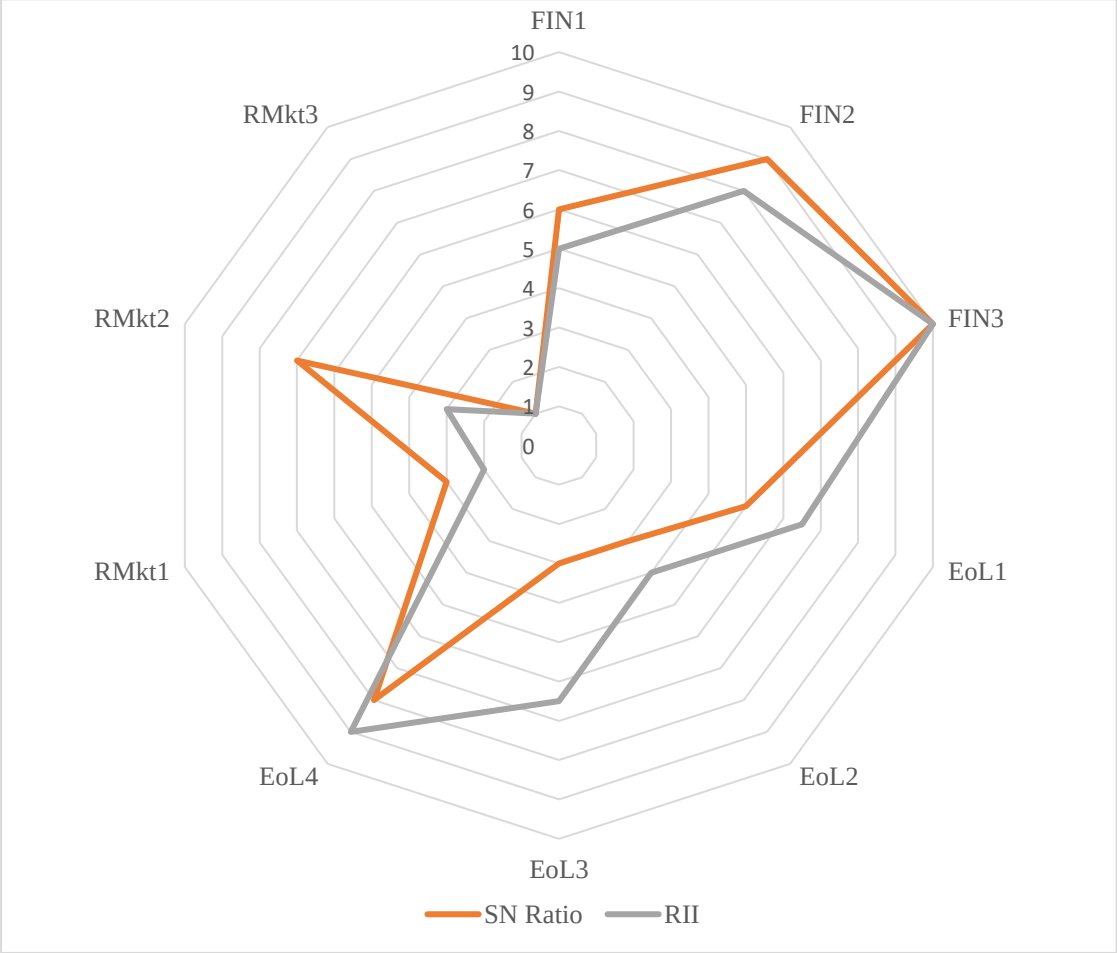

Figure 5.2 Spider graph of SN Ratio and RII ranking of drivers

The measure of Sampling adequacy - Kaiser-Meyer-Olkin (KMO) value was 0.697 which is high in the acceptable range of 0.5 to 0.7[86-89]. The significance value of Bartlett's test of sphericity for existence of identity matrix in correlation coefficients with chi-square of 129.303 at df 45 is less than 0.001 rejecting the hypothesis.

Both inferences confirmed that the possibility of underlying factors among the different drivers as initially proposed in the classification of drivers. It may be noted that Cost Reduction was found to be the least important driver which implied that the remanufacturing could be profitable, provided the expectations of being “as good as new” were met.

5.2 DEMATEL DIGRAPH:

As a first step towards investigating relationship between factors and drivers a study employing pairwise comparison technique was used. Decision making trial and evaluation laboratory (DEMATEL) technique, first developed by the Geneva Research Centre of the Battelle Memorial Institute is used to envisage the structure of causal relationships through digraphs [90]. Decision making trial and evaluation laboratory (DEMATEL) is used as an effective method for the identification of cause-effect chain components of a complex system in literature [91-97]. In the study, the survey was carried out with participants from On-field maintenance, marketing and design department having more than 3 years of experience in the automotive sector. The nine constructs were ranked pairwise on a scale of 0 (No influence) to 4 (High Influence). The matrix denotes the effect of Row factor on the column factor. It may be noted that in DEMATEL, the elements of diagonal of Direct Relationship Matrix are always considered zero. Direct telephonic communication and online meetings were conducted with the respondents. The Direct Relationship matrix (R) obtained by averaging the corresponding responses is further Normalized and Total Relationship Matrix (T) is calculated. The results of Causal relationship calculations obtained from this matrix help in classifying factors into cause and effect.

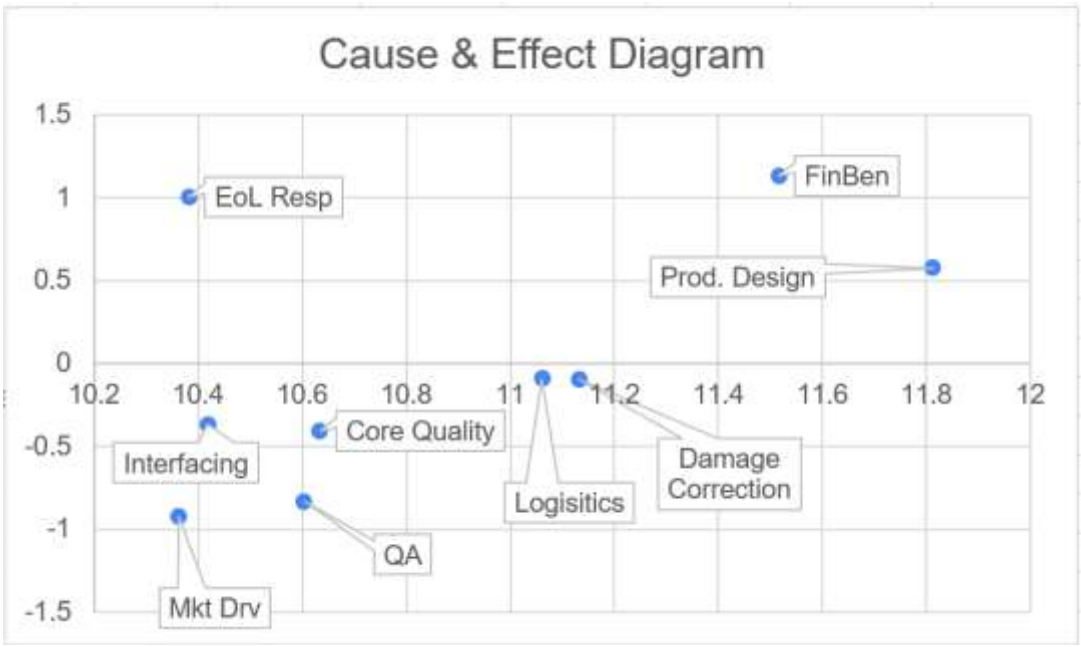

Figure 5.3 Cause and Effect Classification

In the cause-and-effect diagram shown in figure 5.3, the horizontal axis represents the degree of importance. The study indicates that Financial Benefits rank 2nd in importance with highest importance to the Product Design factor. It is observed that Financial Benefit, End-of-Life Responsibility and Product Design are the influencing factors.

To draw the digraph of relationships, the relationships in matrix T having values greater than the threshold value are considered. The threshold value calculated was 0.604452 and the digraph of the relationships thus derived is shown in the figure 5.4.

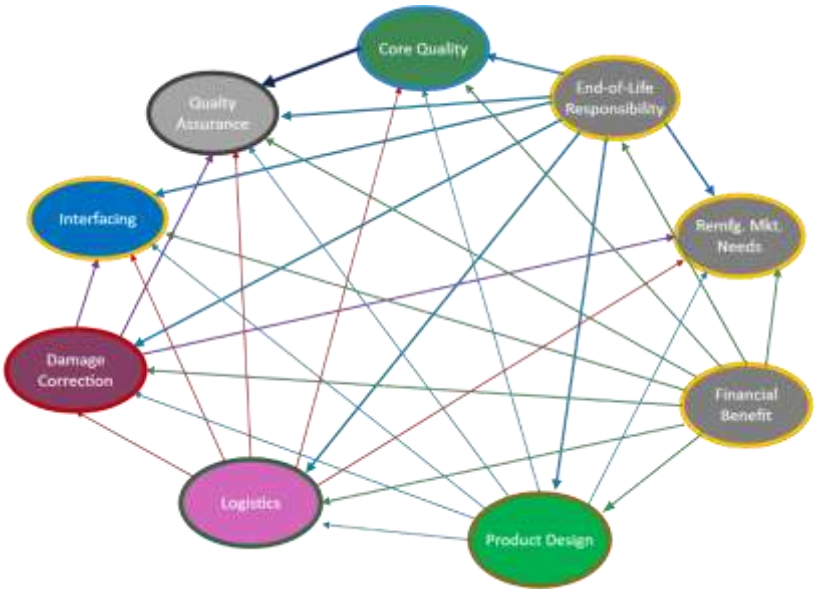

Figure 5.4 DEMATEL Digraph

The digraph obtained through DEMATEL provides a good start as an initial model. However, it cannot be considered a fit model in the absence of evaluation of relationships. With the theory of the relationships thus developed, Confirmatory Factor Analysis (CFA) is recommended in literature [98,99]. Confirmatory Factor Analysis through Structural Equation Modeling is thus employed.

5.3 CONFIRMATORY FACTOR ANALYSIS:

Structural Equation Modeling (SEM) as a form of CFA is a consolidation of multivariate analysis based on multiple regression techniques [100-107].

For this study, a priori sample size calculator was used as recommended in literature [108]. For 9 latent variables and 44 observed variables, anticipating a large effect size (d = 0.50) with a statistical power of 0.80 and a statistical significance of 0.05, the recommended number of samples for model structure was 96. Post development of the model, the minimum sample size is recommended as ten times the number of maximum arrow heads pointing on a latent variable in the structural or measurement model. Applying this rule to the final model, the minimum sample size is 60.

A questionnaire was designed incorporating the above characteristics asking the respondents to rank each of them on a 5 point Likert scale of “Not Important”, “Slightly Important”, “Moderately Important”, “Important” and “Very Important”. WarpPls was used as the SEM software for the analysis as it has the potential to account for real-life non-linear regression. The survey was focused on successful remanufacturing organizations in Automotive industry. The questionnaire was sent by mail to 436 remanufacturing organizations. The respondents spanned three countries majorly - 52 percent from USA, 12.5 percent from Canada and 14.6 percent from India. Few responses from Serbia, Hungary, Finland, Poland and UAE were received too. 64.6% of companies had 50-249 employees, 29.2 % had 10-49 employees and 6.8% had more than 250 employees. 52 responses were from technical personnel including Plants/Operations, Quality & Inspection, Design, On-field Maintenance while the rest of the responses were from higher positions including directors, presidents and owners of the organizations who drive the remanufacturing strategies. The survey was particularly carried out for organizations having remanufacturing activities. The 196 useable responses indicated active involvement of the companies in all the activities.

5.3.1 SEM: Convergent and Divergent Analysis

The first step in SEM is to test the measurement model which is done by analyzing the combined loadings and cross loadings. It was observed from loadings in table 5.4 that the indicators demonstrated highest score under their respective construct, confirming the correctness of categorization. However, it's important that the value of the loading to be acceptable it needs to be more than 0.6 and preferably more than 0.7.

5.3.2 Reliability Testing:

The composite reliability coefficients and Cronbach's alpha calculated for each of the 9 constructs are shown in table 5.5 and all the values are found to be acceptable.

Table 5.5 Reliability Testing

	Fin Bn	EL- Rp	Mkt	CoQ	QA	Int-Fc	D-Cr	Lt	Prod
Composite reliability coefficients	0.826	0.85	0.892	0.907	0.857	0.874	0.843	0.869	0.952
Cronbach's alpha coefficients	0.684	0.735	0.818	0.871	0.777	0.783	0.751	0.812	0.923

5.3.3 Discriminant Validity Test:

Square roots of Average Variances Extracted (AVEs) are computed and shown in table 5.6. The maximum value across row and column are found on the diagonal and are more than 0.7 for the discriminant validity test to be cleared.

Table 5.6 Correlations among Latent variables and errors

	Fin Bn	EL- Rp	Mkt	CoQ	QA	Int-Fc	D-Cr	Lt	Prod
Fin Bn	**0.784**								
EL- Rp		**0.809**							
Mkt			**0.856**						

CoQ				**0.814**					
QA					**0.775**				
Int-Fc						**0.835**			
D-Cr							**0.758**		
Lt								**0.756**	
Prod									**0.932**

After validating the Measurement Model, the structural model is worked upon for testing relationships between the constructs.

5.3.4 Path Modeling:

For the structural model (inner model), paths are drawn between the constructs. Each arrow between construct represents a hypothesis testing the significance of the path coefficient calculated between the constructs. Firstly the effects of the six design factors on each of the three drivers is considered. An example of the same is shown in figure 5.5.

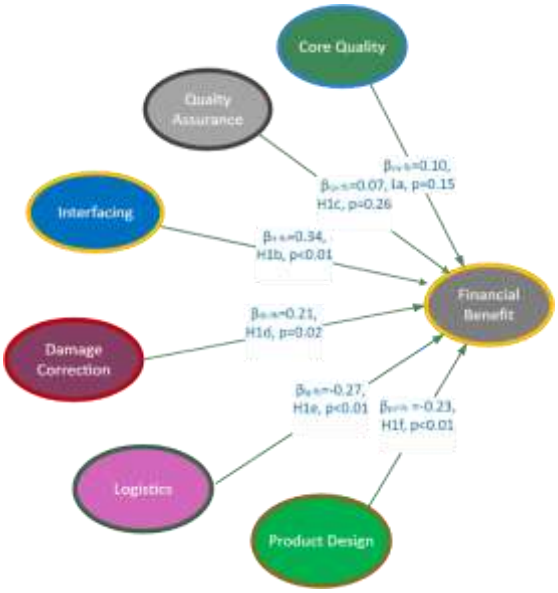

Figure 5.5 Path coefficient of effect of Design factors on Financial Benefit Driver

The valid model based on retention of significant relationships considering the effect of the design factor on drivers is shown in figure 5.6. However, it may be noted that this model doesn't consider the effect of design factors on each other or that of the interrelationship between the drives. It thus needs to be modified further.

Rigorous path modeling is needed at this stage and required careful observations of each iteration to improve the model. A variable can also act as a mediating variable. Initially the

effect on each of the driver by other drivers, on each of the design factor by other design factors and on each of the nine constructs by other eight constructs is computed. Further, besides mediation of each variable in every significant relationship is tested. The research was successful in deriving the most robust model with 19 significant relationship and its quality indices are shown in table 5.7

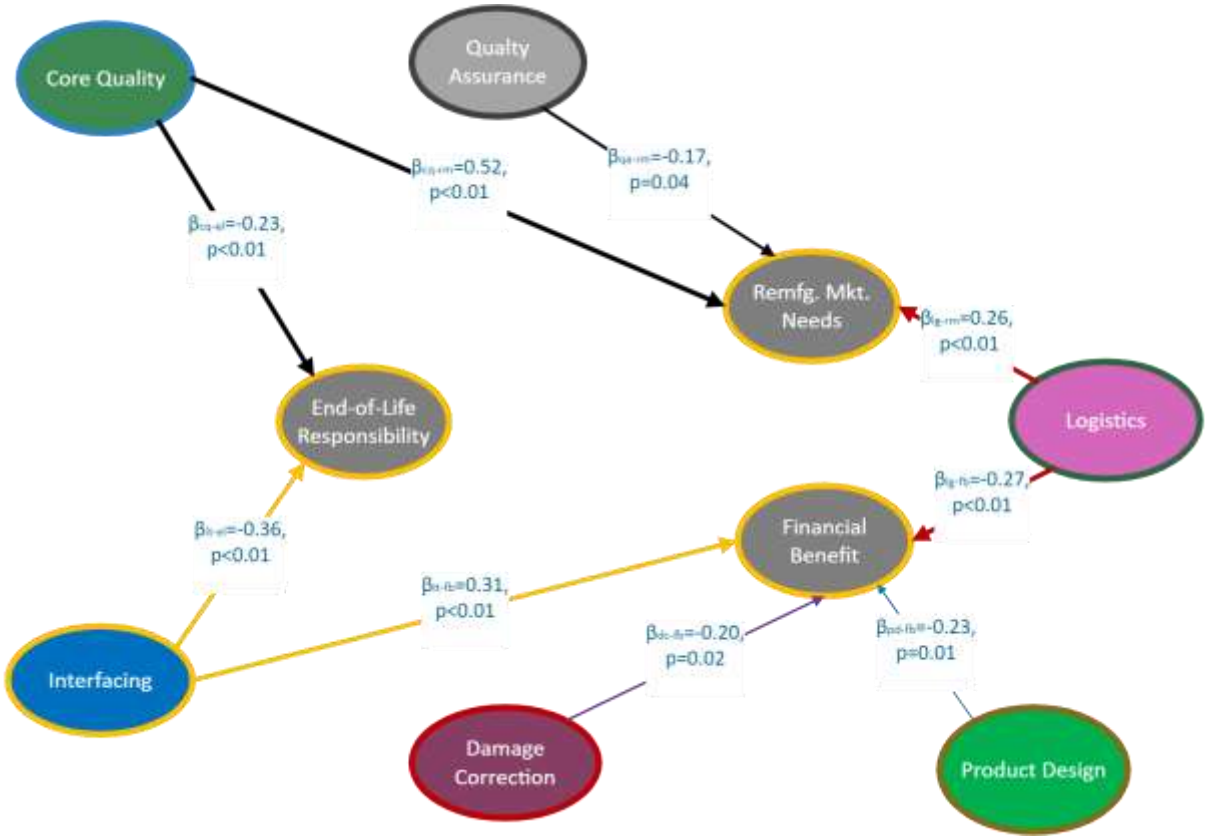

Figure 5.6 Unidirectional model of significant effects of design factors on drivers

Table 5.7 Model fit and Quality index	
Average path coefficient (APC)=0.3	Significant with P<0.001
Average R-squared (ARS)=0.3	Significant with P<0.001
Average adjusted R-squared (AARS)=0.2	Significant with P<0.001
Average block VIF (AVIF)=1.1	Within ideal range of <=3.3
Average full collinearity VIF (AFVIF)=1.6	Within ideal range of <=3.3
Tenenhaus GoF (GoF)=0.44	Acceptable Good of Fit for Large effect
Sympson's paradox ratio (SPR)=0.94	Acceptable as >=0.7

R-squared contribution ratio (RSCR)=0.95	Acceptable as >=0.9
Statistical suppression ratio (SSR)=1.000,	Acceptable as >=0.7
Nonlinear bivariate causality direction ratio (NLBCDR)=0.97	Acceptable as >=0.7

Validity of the model requires all the retained relationships to have p-value to be less than 0.05 and all the model indices to be acceptable. Continuous change in values was observed for each iteration and it was attempted to ensure that maximum number of significant relationships are retained while monitoring the acceptability of the model. The indices shown in Table indicate that the model is acceptable.

However, it may be noted that the model is still complicated and is not readily usable. To "interpret" the model for use by designers, we simplify the model using the Interpretive Structural Modeling.

5.4 MODEL REFORMATION:

The model is further reformed for prioritization. The hierarchical structural is generally preferred for use as it gives clear direction on setting up the priorities. Interpretive Structural Modeling (ISM) is a method to achieve the same and used extensively in literature[109-114]. The Structural Self Interaction Matrix is formed by considering the significant relationships derived from ISM. Its further converted into Initial reachability matrix to which Warshall Algorithm is applied for 9 iterations to derive the Final Reachability Matrix. The Driving Power of the factor is obtained from sum of row for the factor while dependence is calculated by from column for the respective factor.

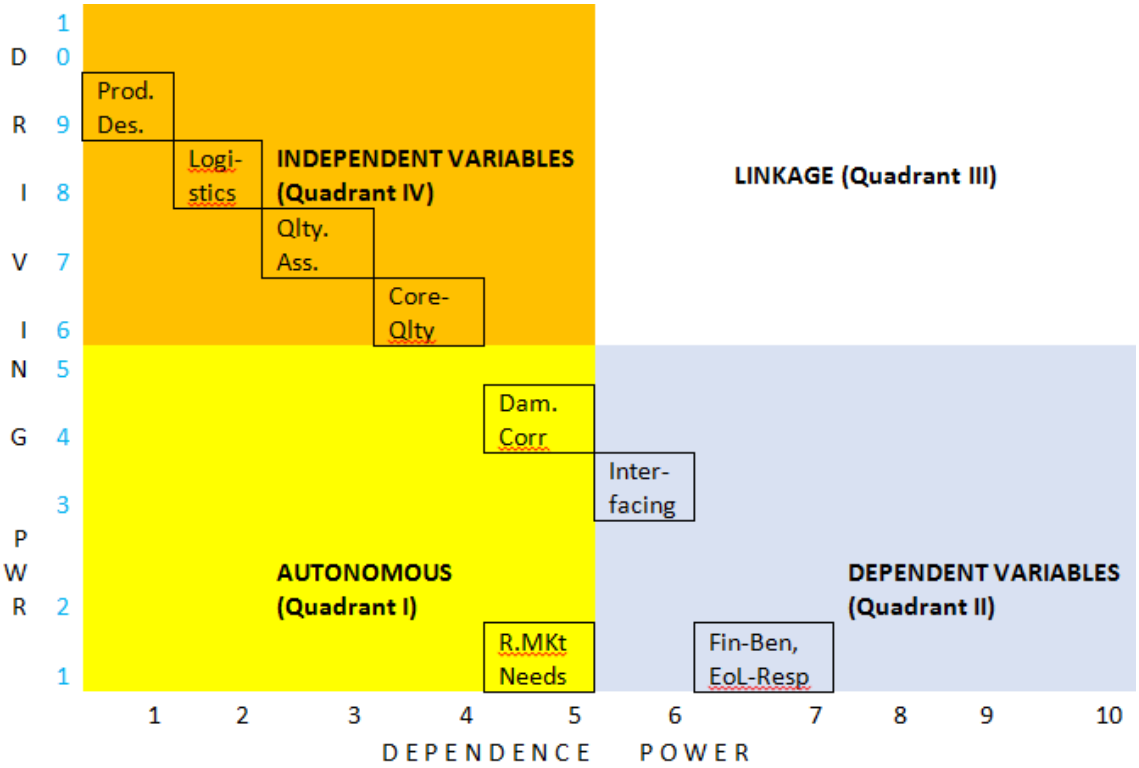

Figure 5.7 MICMAC Analysis

MICMAC Analysis (Cross- impact Matrix Multiplication) based on the driving and dependence power of factors (shown in figure 5.7) provides insight into their nature. Remanufacturing Market Driver has least driving power while Damage Correction may be able to drive factors in the second quadrant. Factors in the second quadrant- Financial Benefits and End-of-Life Responsibility have high reliance and are driven by other factors. Interfacing on the other hand may be able to influence Financial Benefit and EoL Responsibility Drivers. In this analysis, none of the factors lie in the unstable third quadrant. Core Quality, Quality Assurance, Logistics and Product Design have high influence on the other factors. They appear in the lower zone of the hierarchical structure.

Deriving Hierarchical structure:

To prioritize the factors, reachability set is gained from row elements having 1 and Antecedent Set is gained similarly from column elements. The intersection of the two sets is found in every iteration and factors having intersection set equivalent to reachability set are extracted. This helps decide the level of the factor which is then removed from subsequent iteration.

The resulting hierarchical structure is depicted in figure 5.8 :

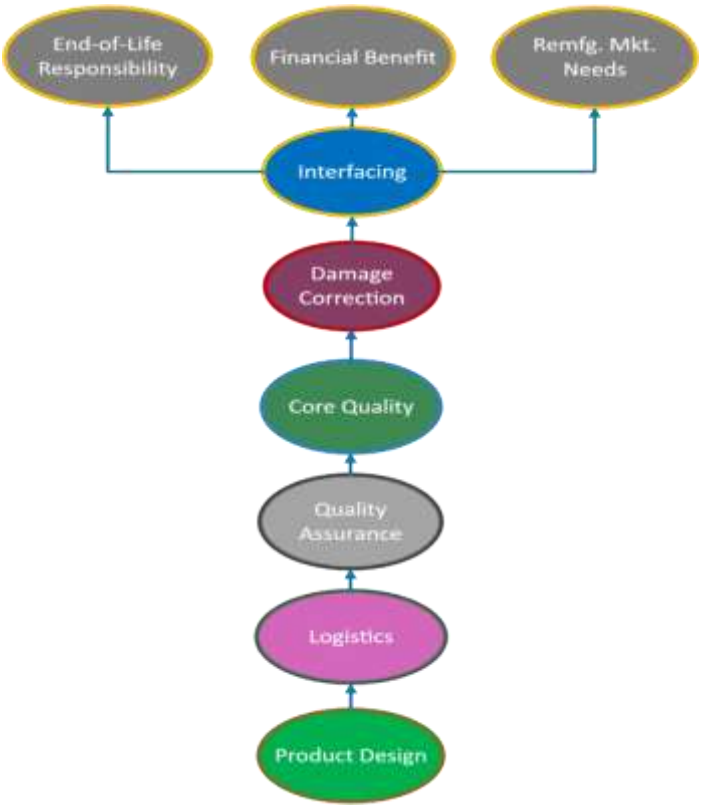

Figure 5.8 Hierarchical Model

The three drivers are found to be at the highest level while setting Product Design goals turns out to be the start point. Ensuring good logistics is primitive for success of remanufacturing considering the need for procuring used products (reverse logistics) as well as of making the remanufactured product available alongside the new counterpart becomes a priority for ensuring feasibility of remanufacturing. Giving assurance of the quality of remanufactured product helps promote its sale and return of used product for reasonable value. To ensure the good quality of returned product (core), the design should provide for protection of conserving value of parts. Designing for better damage correction facilitates the correct choice of the four End-of-Life options for the used product. Assembly and disassembly turns out to be the closest interlinking design factor to the three drivers of remanufacturing success. This model based on best remanufacturing practices in the automotive sector is recommended for use by OEM designers. 19 Hypothesis are found to be valid.

CHAPTER 6
CONCLUSION

The aim of the research was to develop a framework which will aid the OEM Designers to incorporate remanufacturing from the first stage of product development. Examination of literature established that current design aids were of limited use in industry and there was a need for optimized prioritization criteria tool for remanufacturability design considerations. Design considerations useful in assessment of remanufacturability of product design were the requirements identified from literature and existence of underlying factors among the drivers was probed. To develop the tool DEMATEL Methodology was used to form an initial theoretical model of relationships between the Design factors and drivers of remanufacturing. The final model consisting of 19 significant relationships, derived by refining the initial model with numerous iterations was validated by Confirmatory Factor Analysis using Structural Equation Modeling. The framework was simplified further for ease of use by Interpretive Structural Modeling. The study also provides a novel systematic amalgamation of structural modeling techniques to develop robust model.

This study recommends that this framework be used by OEM designers to facilitate the design of the three stages of product simultaneously – New, End-of-Life and Remanufactured. The framework created from the recognition of relationships of best practices provides an insight into the prioritization of design factors and their relationships with drivers of remanufacturing.

CHAPTER 7
FUTURE WORK

The framework was developed for OEM designers in context of automotive sector. The traits of end-users of capital equipment like machinery and industrial manufacturing systems may be relatively different.

The focus of the current research was on “Remanufacturing” option and was inspired by the first three major design aids viz., DfRem metrics, REMPRO Matrix and DfX strategy mapping. The scope of this study may be extended in future to include an appropriate integrated approach with emphasis on possibly planning for other EoL options such as repair, refurbishment and recycling.

PUBLICATIONS

- Naik, S. and Terkar R., "Development of Model of Remanufactured Product Competencies", *International Journal of Mechanical Engineering*, vol.. 7 no. 1, pp.6893-6900,2022.ISSN: 0974-5823 **(SCOPUS Cite Score: 1.2)**

- Naik, S. and Terkar R., "Investigation of Remanufactured Product and End-of-Life Product Potentials from End-user Perspective", vol.7 no.3 pp.307-313, 2022. ISSN: 0974-5823 **(SCOPUS Cite Score: 1.2)**

- Naik, S. and Terkar R., "Role and Significance of Visualisation in Product Design at Prototyping Stage." In *CAD/CAM, Robotics and Factories of the Future*, pp. 625-636. Springer, New Delhi, 2016. ISSN: 2195-4356 (Conference Research Article published in ISSN: 2195-4156) **(SCOPUS Cite Score: 0.6)**

- Naik, S., and Terkar, R., "A study on designing for sustainable product development in view of end-user role through remanufacturing" In *International Conference on Communication and Signal Processing (ICCASP), Advances in Intelligent Systems Research*, pp. 153-159. Atlantis Press (Springer Nature),2016. ISSN : 1951-6851 (Conference Proceedings)

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